Measurement of the loss due to grooved bottom structure intended for use as a backing in Capacitive Micromachined Ultrasonic Transducers

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ABSTRACT

The backing structure mostly used in Capacitive Micro machined Ultrasonic Transducers (CMUTs) is a composite of epoxy and tungsten powder. To be able to absorb the acoustic signals, it should have high acoustic impedance that matches with the silicon substrate (on which CMUTs are manufactured) and it should be lossy. If we are able to make this structure thick enough, then it will damp out the signal in the backing so that it would not reflect back to the transducer. But if we intend to use the transducer in applications where there is no room for the thick backing, for example in IVUS (Intravascular Ultrasound), a groove structured backing could be used [1]. The grooves give extra loss by scattering the waves so that a thinner backing would be enough. The scattering removes power from the specular reflection from the back surface. This reflection is otherwise harmful for the imaging. In this paper, we will present how to make such a structure. Moreover, we will present some experimental results to show that this type of structure reduces the specular reflection and compare the obtained results with theoretical calculations. It is shown that the desired reflection level for an imaging application is obtained over a wide range of frequencies around 20MHz using an absorber thickness of 200µm.

INTRODUCTION

Ultrasound transducers need an acoustic backing that ensures that any acoustic signal which propagates from the transducer into the backing is absorbed in the backing such that they are not reflected back to the transducer and create false echoes.

The backing material mostly used for ultrasonic transducers is a mixture of epoxy and tungsten powder. To be able to absorb the waves, the acoustic impedance of the mixture must be equal to that of the silicon substrate of the micromachined transducers and it must be very lossy [4]. If the backing is thick enough, then it will absorb most of the incoming waves. But in many applications, there is little space available under the transducer such that it is difficult to accommodate a sufficiently thick layer of material with high propagation losses. Irregular structures at the bottom surface are customarily used to scatter the waves. Here we will look at a systematic way of structuring the back surface in a way that takes little space such that it scatters the waves into waves with significantly changed propagation directions. This reduces the specular reflection, and gives long propagation paths back to the transducer for the waves. It may also convert the waves to shear waves in the backing, which normally have much higher propagation losses in the backing material than the incoming longitudinal wave.

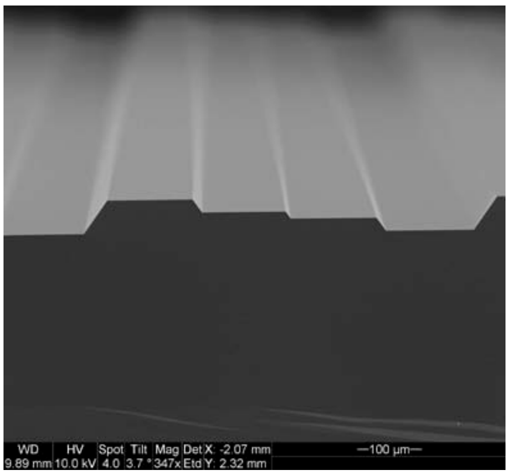
If the irregular structure consists of parallel rectangular grooves with equal width and spacing of the grooves, it gives cancellation of the specular reflection of the waves when the groove depth is ¼ of the acoustic wavelength at broadside. This will cause strong scattering in a narrow band. The scattering can be extended to a broader frequency range by superimposing grooves with different depths and different periodicities. The principle is to provide sets of reflecting surfaces with equal areas but different depths that may be grouped in pairs such that the depths differ by a quarter of a wavelength at a set of frequencies, where high scattering is desired. Cancellation of the specular reflection at two independent frequencies requires four different depths; at three frequencies it requires eight different depths. In this paper, we have implemented a structure that gives cancellation at two independent frequencies [1][5].

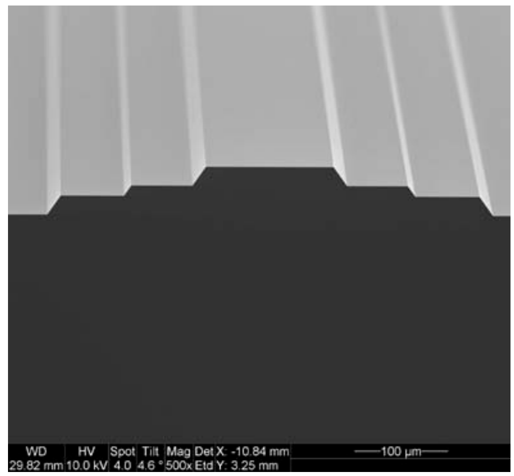
The grooved backing structure discussed in this paper is constructed by molding the composite of epoxy and tungsten on a patterned silicon wafer. Acoustic measurements are performed on such grooved structures. Measured results are compared with theoretical calculations made for this kind of structure.

MATERIALS AND METHODS

There may be different ways to create the desired type of grooved structures, such as laser micro milling, electric discharge machining (EDM), etc. Here an etched silicon wafer is chosen as a mold for making the grooved structure because of its simplicity compared to other technologies. Wet anisotropic etching of a silicon wafer with TMAH (Tetra methyl ammonium hydroxide) is implemented to create grooves because it gives smooth walls compared to other etching techniques but one possible disadvantage of this method is that it creates the smooth wall at 54.7º with <100> plane and there is a small undercut. Simulations are performed on this kind of periodic structure in MATLAB using delay difference of the waves. This result was verified by implementing a FEM model for simple periodic structures using COMSOL MULTIPHYSICS (version 3.5a) [1]. The dimension of the structure and the depth of etching were estimated to give cancellation at two independent frequencies.

The structures prepared by anisotropic wet etching of silicon wafers were close to the design parameters used in the simulations. There were little variations around the edges and the variation of the step heights were within the tolerance limit of ±5 to ±10%. For the cancellation of specular reflection at two frequencies, the width of each step should be one fourth of the total period. But as we used the wet etching technique, the widths of different steps were reduced to some extent compared to the period to make them equal. Three masks are used for the creation of four step heights in the wafer. SEM pictures of the wafers after the third and the final mask are shown in the figures below.





(a) *(b)*

Fig.1. Etched silicon wafer after the third and final etch for (a) asymmetric design (b) symmetric design.

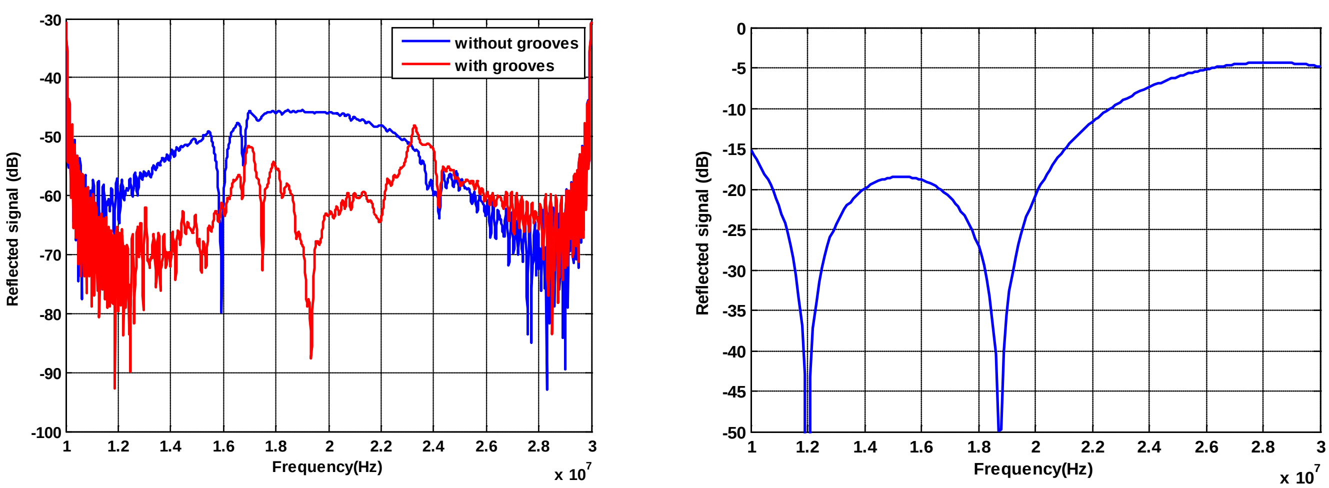
For this particular case, the quarter wavelengths are chosen to give cancellation at 16 MHz and 25MHz for the epoxy and tungsten mixture. The velocity for the epoxy and tungsten composite was estimated to be 2000m/s using the Devaney model for composite materials assuming 48% tungsten by volume [6]. The structure is periodic with a period of 600 microns. The different depths measured were 20microns, 31 microns and 51microns. Epoxy used in the measurement is EPO-TEK 301-2 from Epoxy Technologies. The tungsten used in the experiment are mixtures of powder tungsten with different sizes (<1micron and 1-5microns) from Alpha Aesar company.

To estimate the loss due to the grooved structure, reflection measurement was performed using Rhodes and Schwarz's vector network analyzer. Immersion type ultrasonic transducers from Olympus (Panametrics-NTD V300 series) with centre frequency 20MHz were used for the experiment with the frequency swept from 10MHz to 30MHz. The obtained results were post processed using MATLAB. Although the groove depths were optimized for the epoxy-tungsten mixture, the structures were also tested for wave propagation in water and epoxy (without tungsten). The parameters in the simulation were adjusted to give the estimated response for each case.

RESULTS AND DISCUSSION

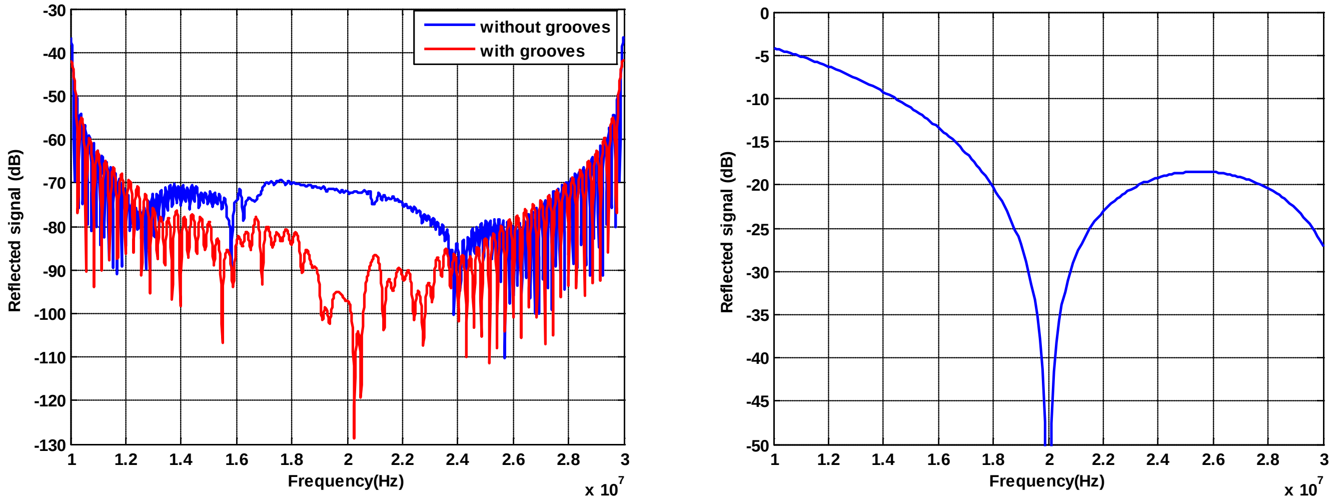
Acoustic measurements were performed with the grooved structure in different cases. In the first experiment, the reflection from a grooved silicon wafer, which was immersed in water, was measured with acoustic waves irradiated on grooved side. The results are shown in figure 2. The silicon wafers used in the measurements are 500microns thick. The experiment was repeated with a silicon wafer with the same thickness but without any grooves. The theoretical estimate of the reflection loss in water, taking velocity of water as 1500m/s, is also shown. It can be seen that the there is significant reflection loss due to grooves at 19MHz. From theoretical estimate, we would expect another dip at 12MHz. But from the measurement, we can see only a modest dip at this frequency. This is due to the reason that the signal to noise ratio is poor outside the 12-26 MHz range as 6dB bandwidth of the transducer is 48%.

In the second case, the experiment was repeated with thin epoxy layers on silicon wafers. The wafers with epoxy were kept in water and irradiated with acoustic waves from the epoxy side, other side remaining free. Also in this case, the experiment was repeated with a silicon wafer without grooves. The results are shown in figure 3. We can see significant reflection loss near 20MHz which matches fairly well with the theoretical estimate. The thickness of epoxy was kept the same, 1 ±0.1mm, in both cases. Since the losses in the epoxy are very high, the signal to noise ratio is also poor in this case. From our experiment, the losses in epoxy are estimated to be 9-12dB/mm at 20MHz. For the theoretical calculation of reflection loss, the longitudinal velocity of epoxy is taken as 2500m/s. Both in the experiments with epoxy and water, dips could be seen in the curves at 16MHz and 24MHz. They are due to plate resonances in the silicon wafers. The resonance is supposed to occur at an integer m times 8 MHz ($f=m*v/2t$, velocity in silicon, v= 8000m/s and thickness, t= 500microns), which fits well with the measurements.



(a) *(b)*

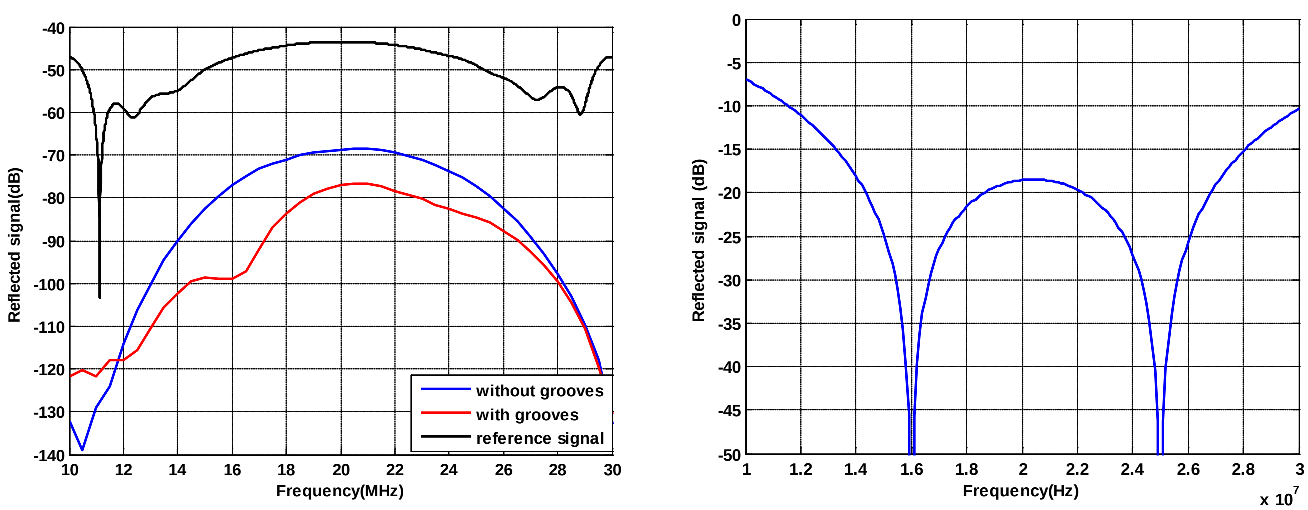
Fig.2. Reflection measurement with anisotropically etched silicon wafer in water (a) experimental result (b) theoretical estimate



(a) *(b)*

Fig.3. Reflection measurement with anisotropically etched silicon wafer with epoxy in water (a) experimental result (b) theoretical estimate

The third experiment was performed with a mixture of epoxy and tungsten. The tungsten powder (mostly 1-5microns size and some <1microns size) was mixed with epoxy at about 40% volume fraction to get a longitudinal velocity around 2000m/s and an acoustic impedance of 12MRayl. The mixture was cast between two silicon wafers. Two samples of equal thickness were prepared, one with grooves and one without grooves. It was cured at room temperature for 24hous. The silicon wafers were covered with a thin layer of polymer so that it could easily be removed from the cured tungsten and epoxy mixture. After it was released from mold, similar measurements were repeated as in the other cases.



(a) *(b)*

Fig.4. Reflection measurement with epoxy and tungsten mixture (a) experimental result (b) theoretical estimate

As the losses in epoxy tungsten mixture is very high (30-40dB/mm as estimated from the experiment), a 200micron thick layer is used to estimate the loss due to the grooves. As the structure was thin, the echoes from the front and back surface of the specimen were superimposed in the time domain response; so it was difficult to distinguish them. To obtain the shape and level of the reflected signal from the bottom surface, we made similar reflection measurements from a single reflecting surface to get a reference signal. This signal was matched in amplitude and phase with the first part of the echo, and then subtracted from the time domain responses that we got with the epoxy and tungsten structures. In this way, we obtained an estimate of the echo from its back surface. This was done for both composite structures. These calculations assume that the epoxy tungsten mixture behaves like a uniform medium in the frequency range of interest. The experimental results along with a theoretical estimate of the scattering losses are shown in figure 4. It can be seen from the figure that there is significant additional reflection loss due to the grooves, about 25dB, around 16MHz, and about 10dB or more in the frequency range of 14MHz to 24MHz.

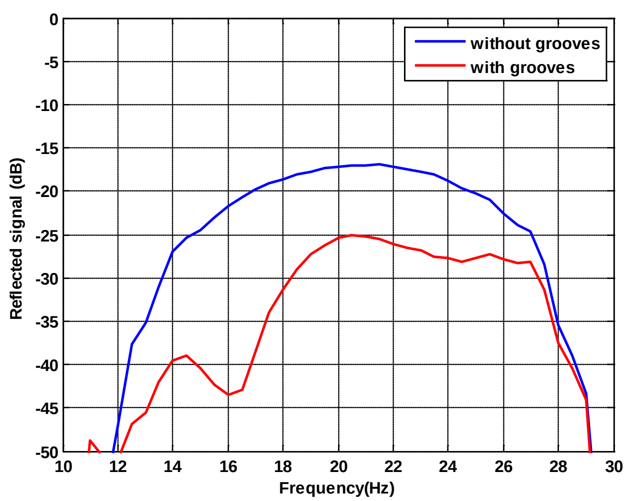


Fig.5.The relative reflected signal at the top of the tungsten epoxy composite with and without the grooves at the bottom

Figure 5 shows an estimate of the difference in amplitude of waves going downwards and upwards at the top of the epoxy tungsten composite, both with and without grooves. This was obtained by subtracting the measured reflected signal from the bottom surface from reflected signal from top surface, and subtracting two times the transmission loss through water-composite interface, 2*4.03dB. The latter is calculated by taking the acoustic impedance of water and epoxy tungsten mixture as 1.5MRayl and 12MRayl respectively. As the noise levels are high outside 12-26MHz range, the results outside this range are somewhat uncertain.

SUMMARY AND CONCLUSIONS

From the experiments, we are able to verify that the grooved structure at the bottom of the backing provide additional losses compared to a planar bottom surface. The experimental result matches fairly well with the simulation and theoretical calculations. With around 40%volume fraction of tungsten in epoxy, we were able to get additional loss of 10-20 dB in the frequency range of operation, with maximum loss of around 25dB at 16MHz, where it was designed to have a null. We would also expect additional loss at 25MHz, which is another frequency designed to have a null. At this frequency we however observe only a modest dip. One possible explanation for this could be that the top and bottom surface of the grooved structure were not exactly parallel.

Thus we can conclude that the grooved structure helps to remove the ringing effect that is encountered with most of the micromachined transducers.

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REFERENCES

1. Kamal Raj Chapagain and Arne Rønnekleiv, 2009, Minimizing the Bottom Reflections in Ultrasonic CMUT Transducer Backing Using Low Profile Structuring, Proceedings of IEEE Ultrasonic symposium.
2. Haifeng Wang et al, 2001, High Frequency Properties of Passive Materials for Ultrasonic Transducers, IEEE transactions on Ultrasonics, Ferroelectrics and Frequency Control, 48, 78-84
3. Martha G Grewe et al, 1990, Acoustic Properties of Particle/polymer composites for Ultrasonic Transducer Backing Applications, , IEEE transactions on Ultrasonics, Ferroelectrics and Frequency Control, 37, 506-514
4. Igal Ladabaum et al, 2005, Microfabricated ultrasonic transducer with suppressed substrate modes, United States patent 6862254B2
5. BT Khuri Yakub et al, 2008, Capacitive membrane Ultrasonic Transducers with reduced bulk wave generation and method, United states patent 7321181B2

6. A.J Devaney and H. Levine, 1980, Effective elastic parameters of random composite, Appl. Physics Letters
7. Keisuke Sugawara et al, 2005, Experimental study of Acoustic properties of (0-3) composite materials for intermediate layer or backing of ultrasonic transducers, Japanese Journal of Applied Physics, 44, 4347-4349
8. C.M. Sayers and C.E. Tait, 1983, Ultrasonic properties of transducer backings, Ultrasonics Journal, 22, 57-60
9. B. A. Auld ,1973, Acoustic Fields and waves in solids, volume II, Chapter 9 on Reflection and Refraction, Book published by John Wiley and sons
10. Chang Liu, 2006, Foundation of MEMS, Chapter 10 on Bulk micromachining of silicon, Book published by Pearson Prentice Hall
11. Panametrics, NDT, Ultrasonic Transducer Technical notes.
12. COMSOL Multiphysics 3.5a Users guide.